Sonification of Particle Systems via de Broglie's Hypothesis

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ABSTRACT

Quantum mechanics states a particle can behave as either a particle or a wave. Thus systems of particles might be likened to a complex superposition of dynamic waves. Motivated by this, the author develops methods for the sonification of particle systems in a logical manner. Many systems and physical phenomena have thus far been simulated, producing a wide range of unique sonic events. The applications that have been explored are for algorithmic sound synthesis and music composition. Of critical importance is addressing the issue of latencies, caused by large complex numerical operations at audio sampling rates. This becomes painfully clear when particles interact with each other. Further applications of this system include scientific sonification, with an appropriate integration of psychoacoustic principles; creating an application for physics and music students to extend and enrich their comprehension of both topics; and inspiring philosophical dialogue regarding the similarities, intersections, and interdependence of Art and Science. Future work aims to produce a real-time application for simulated and real systems, and a deeper integration of quantum mechanics into these techniques.

Keywords

Sonification, physics, algorithmic composition, de Broglie, computer music.

INTRODUCTION

In quantum mechanics (QM) particles and waves have identity crises because one can act as a particle or a wave; and when not a particle, its "matter-wave" has a frequency proportional to its kinetic and relativistic energy.[1] Motivated by this, and some similarities between QM and time-frequency analysis (TFA),[2] comes the idea that signals can be represented and synthesized by an dynamic system of particles construed as waves. Vice versa, a sound might be "materialized" into its corresponding system of particles, and modifications made in that domain to synthesize variants.

Essentially what is developed here is a technique of sound composition using classical many-body mechanics with the most natural mapping of parameters. Such a direct mapping of both multi-dimensional fields not only allows an interchange of concepts to enrich both, for instance sonifying particle collisions for musical purposes, but also enables an additional level of comprehension of the underlying physical concepts—an important goal of sonification [7]. Consequently, when using this technique for composition and synthesis, the composer must also possess skill in physics to do an effective job. Interestingly, it has been observed that, when composing with these techniques, the compositional and scientific concerns merge into the "composerscientist"—a state of thought where physics and music become identical. It has also been found that the audience need not be versed in physics to appreciate or enjoy what they hear; however, more compositions need to be developed to explore this experience.

Apart from these concepts, some problematic issues currently exist in the system and its execution. The computational complexity required for physical particle simulations can be enormous, and when compounded with requirements for audio, there is a large latency period between execution and resultant signal. If precaution is not taken, one is at risk of spending several hours for a sound that could have more easily been produced, albeit without a "physical" correspondence. It can be said that even if a simple sound were created, one would hear it differently because of what it represents. Thus there exists a programmatic issue, whereby a composition developed through this technique might only be interesting within this context. In addition to these, psychoacoustic principles have yet to be integrated to facilitate a more perceivable and precise audification of the system. These issues, and more, will obviously be addressed in future work.

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[1] Hereafter referred to as the *energy* of the particle.

[2] For instance, both QM and TFA employ Fourier transforms, and consequently have uncertainty principles.

AUDIFYING MATTER, MATERIALIZING SOUND

Physicist Louis de Broglie made a famous conjecture in 1923 that particles can act like waves, just as waves can act like particles [1]. He derived the following expression relating the energy of a particle to its matter-wave frequency:

$$\nu = \frac{E}{h} \tag{1}$$

where E is the energy of the particle, and the quantum constant, $h \approx 10^{-34}$ J s, is hereafter set to 1. A particle of mass m_o, and velocity v, has an energy defined by Special Relativity as

$$E(t) = T(t) + \Gamma = \frac{1}{2}m_{rel}v^2(t) + m_o c^2 \approx \frac{1}{2}m_o(v^2(t) + 2\gamma) \tag{2}$$

where $T(t)$ is the kinetic energy, Γ is the relativistic energy, m_{rel} is the particle's mass in motion, and c is the speed of light. To simplify things $v \ll c$ so that $m_{rel} \approx m_o$; and c^2, a very large constant, is replaced by γ, a smaller user-defined constant. With de Broglie's relation and equation (2) a particle can represent a frequency by its energy. Thusly an increase in energy is an increase in frequency. However it might be observed that a potential shortcoming of this correspondence is that linear frequency sweeping isn't perceived as linear. In fact as the velocity of a mass approaches the speed of light, the energy required to increase its speed approaches infinity, just as a larger increment is required to make a perceivable change to a higher frequency. This interesting coincidence might make this shortcoming a blessing when considering relativistic particle systems.[3]

Having corresponded frequency to energy, what is to be done about amplitude? One of the peculiar aspects of particles acting as waves, is that they are not *really* waves; they are some creature that has mutually exclusive properties, but not all the properties of waves or particles. Computing the amplitude of a matter-wave is not straight forward, and doing so leads to an imaginary quantity with no sensible physical interpretation. Instead, by evoking an observer and correlating amplitude to the physical separation of source and receiver a more logical and natural analogue is created. Though this might be a departure from the natural order of physics, a true correspondence is not the aim here. By utilizing mature human perception skills, such as the relationship between loudness and distance, a sonification system is created that is easier to perceive and understand. The relationship employed is the following normalized inverse-square rule:

$$A(d) = \frac{1}{1+d^2} = \frac{1}{1+(\overrightarrow{r_o} - \overrightarrow{r})^2} \tag{3}$$

where $\overrightarrow{r}$ is the particle's position, and $\overrightarrow{r_o}$ is the observer's position.

Combining these results for a system of N particles, considering that matter-waves are sinusoidal, and that superposition holds, produces the following generalized signal:

$$S(t) = \sum_{i=1}^{N} \frac{1}{1+(\overrightarrow{r_o} - \overrightarrow{r_i}(t))^2} sin(2\pi \int [T_i(t) + \Gamma_i]dt). \tag{4}$$

This is the "Equation of Sonic Transformation" and it provides the means for deriving a signal from any particle system.[4] Though equation (4) is explicitly sinusoidal, it is possible that other sample tables could be used, perhaps describing different types of particles, which are read at the matter-wave frequency.

Application of the sonic transform to an elementary signal reveals further enhancements. The most simple signal, a constant amplitude sine wave, $s(t) = A_s sin(2\pi \int \nu_s dt)$, can be quickly materialized to its classical particle-system equivalent. Comparing $s(t)$ and equation (4), a single particle with a constant energy and distance will suffice. Physically this means that there are no forces acting upon it in such a way as to change these properties. At least two possibilities for the corresponding system are: 1) the particle is motionless with respect to the observer; 2) the particle is *circling* around the observer with a constant velocity. Sonifying the latter situation now requires a spatialization algorithm. This is accomplished by taking advantage of the particle positions.

To accomplish this, the space of the system, e.g. the x-y plane, is divided into some number of quadrants, perhaps centered around the observer, where each quadrant is represented by a speaker. For instance, in the x-y plane the region $(x > 0, y > 0)$ might be the front-right speaker in a quadraphonic system. When a particle is in a quadrant, its sonic identity is heard in the corresponding speaker. Problems arise however when considering movement between quadrants, where the sound suddenly switches from one speaker to another. In experience sound flows smoothly from one place to another. This is done by giving

[3] Might also the Nyquist frequency be likened to the speed of light: the greatest frequency that no others can surpass in a given sampled universe?

[4] The absence of a phase term is due to the fact that no logical correspondence has yet been found. Future integration of psychoacoustics will likely make use of it.

each particle a “Sphere of Sonic Influence” of some radius, which contains its sonic identity. When a particle begins to move between quadrants the amount of sound in the speakers is determined by the percentage of the sphere in each quadrant. The signal is placed in each speaker and amplitude scaled by these percentages. *Figure(1)* shows a particle located at some (x, y) with sonic influence in all four quadrants. An observer situated at the origin would thus hear most of the particle in the front-right speaker.[5]

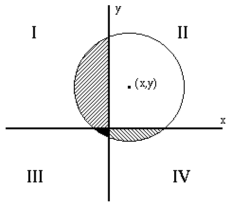

Figure 1: Sphere of Sonic Influence within the Four Quadrants

Making motion even more realistic, the size of the sonic sphere’s radius is related to the separation of the particle and observer such that further particles are perceived as moving slower between quadrants. To further accentuate a sense of motion a Doppler effect has been incorporated. Thus far experiments have only made use of stereo and quadraphonic systems. Further work will experiment with larger sound arrays, and incorporate a head-related transfer function (HRTF) so that this system can be employed on a majority of sound systems.

Expanding these sonification relations for more interesting musical use, modifications to the observer can be made, such as focus, instrument noise or defects, and filters, not to mention changing the system by the act of observation. Focusing on a small region of the system is akin to granular synthesis [8], where particles flying through the aperture are only observed for a short time. These modifications seem an appropriate thing to do since QM states that the observer and the observed can never be independent. The system might even be made more scientifically realistic when considering that raw data is not good data. Thus data reduction schemes might be implemented to create further modifications to the signal, perhaps invoking a justified artistic license.

Among the qualities of this mapping, there is no dependence on a predefined quantized tonal language, e.g. diatonic; it uses any and all frequencies within the audible range. This not only leads to a unique musical language, but provides a result which is quick to visualize and resolve upon audition. Like a mapping of increasing temperature to increasing pitch [9], the correspondence of higher energies with higher frequencies is common sense. Other than the correlation of transverse matter-waves with longitudinal sound waves, there seems to be no arbitrary assignments. This, however, becomes problematic when QM necessitates matter-waves to be sinusoidal; spatial perception and motion is more difficult to perceive with simple spectra sounds. Further work will address this issue by employing dynamic sample tables with complex spectra.

THE SOUND OF A HEATED GAS, AND OTHER USEFUL SONIFICATIONS

With an adequate mapping of particle systems to sound, it is possible to derive signals from physical principles by sonifying scientific phenomena. Any number of systems can be created with many dynamic parameters, and phenomena can be invoked at will. Simulating particles in potentials, such as linear or harmonic, make unique dynamic systems. A linear potential can be imagined as marbles rolling on a slant; while a harmonic potential is like the bowl in *figure (2)*. Each produces unique effects that depend on the particular potential constants. A harmonic potential, unlike a linear one, guarantees the system will remain “stable” since the particles have finite energy limits, and thus might be used to avoid aliasing.

The sonic transform of an N-particle Newtonian, non-interacting, one-dimensional harmonic system, with the observer at the minimum is:

$$S(t) = \sum_{i=1}^{N} \frac{1}{1 + B_i^2 cos^2(\omega_i t + \phi_i)} sin(2\pi[\frac{B_i^2 \omega_i^2 m_i}{4} sin(2\omega_i t + 2\phi_i) + \gamma m_i t]) \tag{5}$$

where $\omega_i = \sqrt{\frac{k}{m_i}}$, k is the potential constant, and B_i and ϕ_i are derived from initial conditions. It should be noted that if ω is sufficiently large, complex frequency and amplitude modulation synthesis are possible—which poses an interesting question for QM: can matter-waves be frequency modulated, making one particle appear as many? Since equation (5) is analytic, the

[5] The quadrant numbers make use of recording convention, where the odd channels are left speakers, the even ones are right, and the first two channels are front.

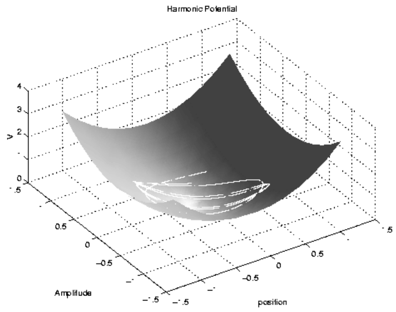

Figure 2: A Two-Dimensional Harmonic Potential

state of the system can be determined at any time. However, when considering time-variant potentials, discontinuous boundary conditions, or particle-particle interactions, the solutions become exceedingly complex necessitating the use of numerical integration schemes, such as the Fourth-Order Runge-Kutta algorithm [2], as well as complete simulations up to the times of interest.

Phenomena such as interactivity, radioactivity, and gas thermodynamics make for novel compositional tools via these sonification methods. With the Coulomb (electrostatic) force the particles are heard pushing each other around; sometimes one pops to a higher frequency which means a particle came too close to another. Collisions are much different because of the abrupt exchanges of momentum within the system; these create chaotic microtonal "organ improvisations." Viscous fluid, and any number of mysterious forces, can be applied to a system, creating drag forces and keeping the system under, or out of, control. *Figure (3)* shows two particles radioactively decaying, which produces distinguishable sounds that have been compared to those in zoological monkey houses. A gas can be placed in a container and heat applied to the walls, creating a very perceivable sonic representation. Perhaps two different kinds of particles, represented by two different sample tables, can react with one another. When two particles form a molecule, their sample tables are convolved. Many different and interesting possibilities exist—a direct result of combining two rich, multi-dimensional disciplines.

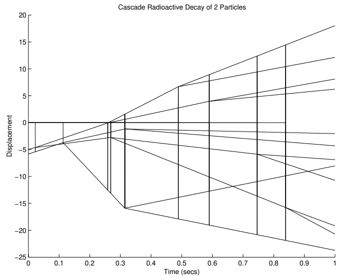

Figure 3: A Cascading Radioactive Decay

These algorithms have been prototyped under a Linux environment using MATLAB 5.0, with computers having processor speeds of up to 500 MHz. It is of concern, and understandably so, that since the present algorithm is doing particle simulations at audio sampling rates of at least 9,000 Hz, there exists a large latency period. This period increases when the set of particles increase, but becomes annoyingly large when continuous particle-particle interactions are simulated—on the order of 10 hours for 1 second of 44.1 kHz, 32-bit, 4-channel, sound from 50 like-charged particles. Further work will address these computational issues by possibly employing interpolation schemes to derive high sampling-rate sound from lower sampling-rate simulations.

CORPUSCULAR COMPOSITION AND THE COMPOSERSCIENTIST

Just as in physical modeling synthesis, physics is at the service of the composer creating innumerable possibilities. However, here the composer has become restricted by the mathematics and methods of physics, and the scientist a slave to the aesthetics and methods of music. Thus in order to employ these techniques in a musically effective way one needs both scholarships. To explore the compositional usefulness of this sonification technique the author composed *50 Particles in a Three-Dimensional Harmonic Potential: An Experiment in 5 Movements*.[6]

[6] Premiered at Stanford University, May 1999.

The four-channel experiment has five 2-minute sections, each of which involve specific phenomena and observation parameters. There are no pauses between movements; each begins where the previous one ends. Because of this the initial state will have a large influence on all subsequent ones. The piece was computed with 32-bits of dynamic range, at a 44.1 kHz sampling rate.[7] The first movement, *Gradual Introduction of 50 Particles into System; Tuning the Harmonic Potential; Adjusting the Observation Apparatus,* is the "promenade of the particles" into the experiment. Entrance times, positions, and initial velocities were determined from uniform random distributions with predefined limits. The second movement, *Adding Viscous Fluid to Reveal the Restmass Spectrum*, makes the particles gradually sink to the potential's minimum energy by the end of the movement. The third movement, *Sudden Increases in the Coulomb Potential of the Universe*, is science-fiction but creates a wonderful contrast to the preceding movements. Every particle briefly sees every other particle and is repelled away, creating a chaotic, spatially expansive, and heart-jumping experience. The fourth movement, *Two-Generation Cascading Radioactive Decay,* is the climactic degeneration of the original 50 particles into 200, and employs an oscillating observation apparatus—for reasons still unknown to the author. In the fifth movement, *Reduction of the System Via Least Energies*, an exciting force is employed, and gradually lower-energy particles exit the system through an expanding hole.

At every stage of composition, there were scientific *and* compositional concerns to work out. Since there is no precise control over what frequencies, dynamics, or timbre will occur when, compositional rules were limited to possibilities, as is the case with many algorithmic compositional methods—not to mention QM in general. However the author did not compose blindly. Several steps were taken to insure that the resultant movement, which took on average 25 hours to compute, would be interesting and useful. This consisted of repeated experiments at very low sampling rates producing graphical representations of particle energies throughout the movement. Changes to parameters and variables were made accordingly.

The overall result makes for an unique and successful musical language, and provides insight into the similarities of Art and Science. The two blended to such an extent during this compositional experiment that the author became a "composerscientist," sharing concerns intrinsic to both disciplines, while solving problems in both domains simultaneously. Since the entire computation was non-analytic, small indeterminate perturbations in the introduction of the piece would have consequences for later sections. Thus this particular composition can be seen as one in a manifold composition, consisting "of all actual and potential variants of a musical work" [5]. Future work will include composing variations on the themes of *50 Particles*.[8]

CONCLUSION

During the development of this system, the author was aware of few other algorithmic synthesis and composition techniques heavily based on science and mathematics, and nothing was known about sonification.[9] Perhaps the most well-known are those developed by Iannis Xenakis based on stochastic principles [10] and Gabor's acoustic quanta [3], and further elaborated by Curtis Roads [8]. The granular synthesis techniques that resulted might be confused with the technique herein presented, precisely from a sharing of the term "particle." There exists fundamental differences between the methods in many respects, but interestingly they both conjure affective pictures of sounds as gases, or processes like evaporation. However, whereas granular synthesis is based upon principles of hearing, this technique is based upon principles of analogy and sonification.

From a compositional standpoint, it could be said that the work done to produce some of these sounds is unjustified because they could more easily be produced by randomly varying oscillators and their amplitudes. It might also be said that this system is only a novel control-data generator for additive synthesis. Though both are somewhat correct, the metaphor, the visualization, and the idea of perceiving realms inherently imperceptible, dissolves. This point can be made clear by including an animation of the evolving system with its sound. The point is conceded that part of the beauty in this system is derived from a programmatic aspect, e.g. that it would be experienced differently apart from its background. But it is from this very basis, sounds represented in particle systems, physics in terms of music, that allows new and intriguing concepts to enrich both fields. Whereas before, it made no sense to speak of two sounds reacting, now it does; and several philosophical issues are inspired, such as the purposes and relationships of Art and Science. Even if some of the sounds produced by this system are simply dynamic sine waves, there exists a higher plane of interpretation of what that signal means, but of course only in this context. It is a matter of hearing a sound, or experiencing the personality of something smaller and larger than life.

This system's use as an algorithmic composition tool has been demonstrated, but what of its synthesis abilities? Considering Jaffe's evaluation criteria for synthesis techniques [4], it doesn't fare well at all. From the correlations of signal properties to abstract physical principles, the parameters are only intuitive to a physicist, and sometimes ill-behaved, or cause inaudible changes. From the fact that large numerically complex systems are being simulated at high sampling rates the algorithm is hardly efficient, and the latency can be astronomical. More development is needed to determine the system's practicality for representing pre-existent sounds—materializing a signal so to speak—and then creating derivative sounds. Perhaps the only

[7] The piece took well over 140 hours of computation time, with the third movement taking about half that because of brief (100 - 3000 ms) particle-particle interactions.

[8] Not to mention, *50 Particles the Musical*, and *50 Particles on Ice*.

[9] Thanks to Jonathan Berger and Julius O. Smith, III, for the information and encouragement.

positive mark about it is that it indeed has a robust sound identity; but even this can be a problem when many of the results sound too similar. Future work includes porting the prototypes to C++ to better address these issue, and hopefully enable real-time and interactive systems.

From a general sonification perspective it might be said that this system is highly specific because energy is given the most perceivable auditory parameter, frequency. For systems in which energy is not of interest, for example irregularities in a crystal lattice, this system would not be of use. This is of course one of the difficulties in creating general standards for sonification systems which must at the same time be specific enough to meet the demands of the experimenter. But what has been presented here *is* meant to be specific. Thus this work should be examined as an experimental implementation of audification for an enlightened comprehension of particle systems. Furthermore the system so far presented is quite ignorant of psychoacoustic principles, which are indispensable for any analytically useful sonification system. Once these rules are integrated, specifically the Fletcher-Munson equal-loudness curves [6], further research will determine the system's usefulness for analytical sonification of suitable data, and then perhaps it can be made more general.

The physicist will surely interject at this point and comment that what is being simulated is not an accurate model of particle systems. The author's subtle use of de Broglie's hypothesis within a predominantly Newtonian context is not how things interact on the quantum level. This comment is well warranted and points to an interesting developmental issue. When this research began, the author attempted to use the quantum wave-functions of particles to derive sounds, since TFA and QM share the same mathematics. This became exceedingly difficult because of interpretation problems between the two, i.e. how are the probability domains of QM to be reconciled with the concrete frequency- and time-domains? The transition made via de Broglie is much more immediate and has allowed for a proper survey of this technique before further work is done in this difficult direction.

With the apparent accessibility of its results, this technique could be used by students to extend their comprehension of physical principles, while simultaneously exploring aspects of computer music. Many results are both informative and aesthetically pleasant because there is an immediate visualization of a microcosm. Perhaps then these methods could be useful for the sonification of suitable scientific data—the purpose of which is not to replace the traditional means of analysis but to enrich it with new perspectives and tools. Both of these ideas have yet to be explored, as well as the difficult problem of materializing complex sounds into particle-system equivalents. Combining two such systems could allow them to diffuse, collide, react; for the first time a piano could chemically react with a soprano. Though the systems so far dealt with have been simulated, it is conceivable to use a real one. The composerscientistperformer executes the piece in a labstage by performing an experiment. The instrument might be a radioactive gas, or an ensemble of fusion tokamaks; the concert space might be the collision chamber of a particle accelerator. The benefit of simulated systems however, is that the audience doesn't get irradiated.

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